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HOW TO COMPUTE COMPLEX INTERCONNECTED DISTRICT HEATING SYSTEMS,(U)
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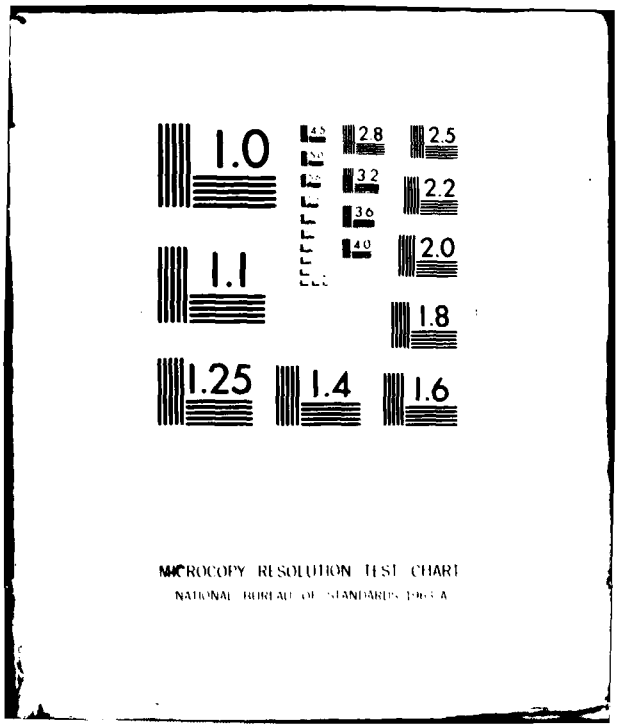
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(6) HOW TO COMPUTE COMPLEX INTER-CONNECTED DISTRICT HEATING SYSTEMS

(10) Rudi/Wehr [redacted] Alfred/Tautz

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The cost-intensive extension of urban district heating systems demands a relatively accurate assessment of the distribution apparatus with respect to the heating market to be supplied. Here we consider the plans of currently available computer programs which can reproduce with practical approximation the operating conditions of complicated interconnected heating networks. Along with the validity of the program, the quality of its application is equally ~'tical; and this application requires a meticulous analysis of parameters such as line resistances, temperature conditions and load distribution.

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HOW TO COMPUTE COMPLEX INTERCONNECTED DISTRICT HEATING SYSTEMS

Rudi Wehr, Dusseldorf, and Alfred Tautz, Dinslaken*

from Fernwarme Int'l, vol. 8 (5), 1979, pp 247-252

1. General

The current rapid extension of district heating systems in West Germany and other European countries is taking place in an arena marked by tension between the requirements of developing public energy policy on one hand and high capital costs on the other.

In considering a prospective district heating project (EVU), whether it be a new system or the extension of an existing one, certain criteria of judgment, more or less in the following order, must be examined in terms of the heating market to be served:

- capital requirements
- operation costs
- operation risks
- flexibility of adaptation
- expansion of energy supply
- utilization of existing power plant heat
- primary energy savings

From the viewpoint of EVU projects, these criteria start with quantitatively definable management and planning factors (capital requirements) and end with quantitatively undefinable public policy objectives (primary energy savings).

In comparison to natural gas, its most direct competitor, the higher use cost of a large district heating system (energy procurement, distribution and consumption), is caused primarily by the five to eight times higher cost of the distribution network. The comparison depends upon:

- the most accurate possible planning of requirements and capacities,
- differentiation among alternative line-connected heating energy carriers,
- computer ascertainment or verification of distribution network operation (ascertainment for new networks or network sections, verification in the case of existing networks),
- load distribution must be considered with respect to the most economical heat sources.

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The present examination concerns itself with the predominant heat carrier - hot water in a dual lead circulation system.

Large district heating systems of this kind are characterized by network inclusion of entire city sections or cities, also by the connection of several heating and power plants, with or without feed from peak load heating plants.

2. Development and Structure of a District Heating System

The increase and expansion of district heating in West Germany is indicated by the values for heat supplied and length of networks over the past ten years, as shown in Figure 1.

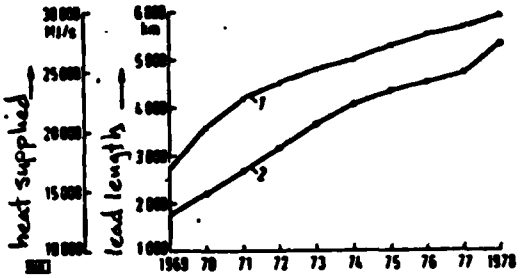

Figure 1. Development of district heating units in West Germany from 1969 through 1978 (source - Arbeitsgemeinschaft Fernwarme e. V.)
1. length of pipe networks
2. quantity of heat supplied

The comparison of large urban district heating systems in Table 1 (end of 1978) shows that there is little correlation between network length and heat supply in present systems.

Table 1. Absolute and relative characteristics of large German district heating systems

city	largest system, each category			customers per km line	supply per km line, Gcal/hr	supply per customer, Mcal/hr
	number of customers	total supply, Gcal/hr[1]	pipe length, km			
Wolfsburg	31,460			160	1.8	11.5
Dinslaken	31,100			115	1.9	16.6
Hamburg		1908		9.5	5.6	591
Berlin		1410		11.0	6.0	549
Hamburg			339	9.5	5.6	591
Munchen			279	15.4	4.9	320

1. figure derived statistically, in part from earlier known values

There are therefore, large systems with low density of supply, which predominantly serve households, as well as large systems with higher supply density which predominantly serve public establishments and professional-industrial customers.

Apart from the relatively few systems of the former type, district heating systems, because of high capital costs, are generally characterized by:

- somewhat restricted area served
- small number of outlets
- high average heat supply
- minimal interconnection
- single feed at middle and low load operation
- congruent delivery and return.

The ascertainment or verification of such relatively simple distribution networks with computer pipeline network calculation is repeatedly discussed in the bibliography (articles 1-6).

With the growth of urban district heating systems through government investment, the above characteristics change, in the direction of:

- increasing surface area served
- growing number of outlets
- decreasing average supply per outlet
- greater interconnection
- combined operation with different heat supplies
- insertion of network pumping plants.

Planning and operation of increasingly complicated distribution networks demands elaborated computer methods for valid modelling of such systems.

3. Network Hydraulic Characteristics

In hot water networks the usual pipe diameters, roughnesses, and flow rates are such that the flow conditions lie predominantly between hydraulic smooth and hydraulic rough. The boundaries of the flow regime, as well as a comparison with cold water network flow characteristics, are shown in Table 2 and Figure 2.

Table 2. Characteristic flow values of water distribution networks for tap water and district heating systems.

Characteristic	medium	hot water	cold water
nominal diameter	DN	20 400	100 600
network roughness	mm	0,1 0,3	0,4 4,0
flow rate	m/s	0,5 3,0	0,1 2,0
temperatures	°C	45 180	5 15
kinematic viscosity	m²/s	0,30 · 10⁻⁶ (100 °C)	1,31 · 10⁻⁶ (15 °C)
Reynolds number	10³	80 4000	15 900

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1. network roughness or apparent roughness equals pipe roughness plus incidental resistances

The flow diagram (Fig. 2) shows that, in comparison with cold water systems, the cost and operation related factors for hot water flow can be significantly more tightly defined.

4. Economically Optimal Pipe Diameter

The various cost components of a district heating system are:

- capital costs
- conveyance costs
- heat loss costs.

Capital and heat loss costs climb with increasing pipe diameter, while at the same time the conveyance costs decrease.

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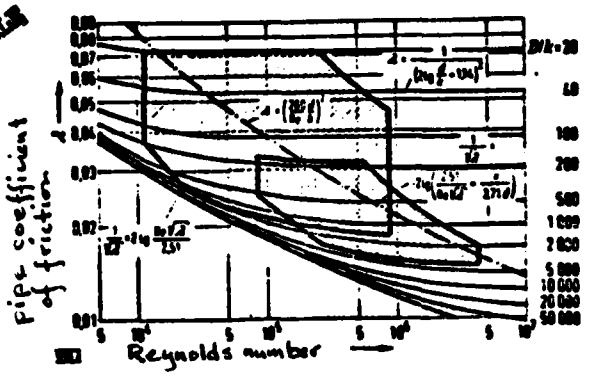

Figure 2. Flow domains for water networks and district heating system networks
cold water ///////
hot water XXXXXXX

These opposing cost/diameter functions lead to an optimal-cost pipe diameter. Since heat loss costs generally lie around or under 10% of combined costs, they can be disregarded in the cost optimization.

Based upon pipe-laying costs as determined for the service areas of Innenstadt, Stadtrand, and Trabantenstadt in a collective study of district heating by the Federal Ministery of Research and Technology, a determination could be made according to required heat delivery, and cost of electricity at that time, of the optimal pipe diameter.

For water volumes between 50 and 100 tons/hr and electricity costs from 5.0 to 16.0 pfennig/kWhr, pipe diameters are calculated such that optimal flow rate is 1.4 - 2.2 m/s. Logically, relatively high pipe laying costs and lower electricity costs would lead to small pipe diameters with higher flow rate, while in Trabantenstadten the more economical laying costs and high electricity costs led to slower flow rates in larger pipes. Over a fairly high range, the most economical water flow rate was 1.8 m/s.

Figure 3 allows a simplified determination of the most economical pipe diameter, given heat yield in conjunction with the temperature spread.

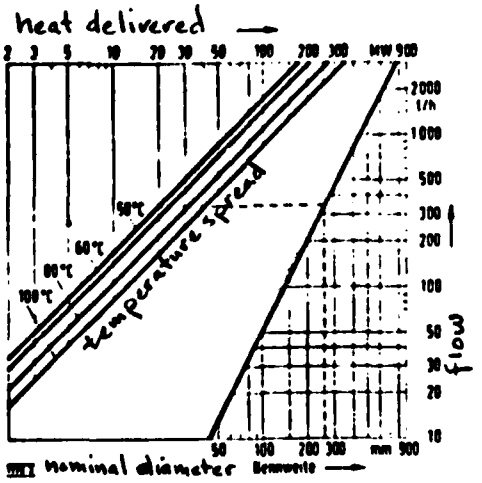

Figure 3. Determination of nominal pipe diameter, as a function of heat capacity at a water flow rate of 1.8 m/s

example:

heat capacity	20 MW
temperature spread	50°C
flow	344 tons/hr
nominal diameter	266mm ≙ DN 250

If instead of the above static cost conditions a dynamic analysis is required, the rising cost of electric power must be taken into consideration.

The capital cost of a line may be considered as a fixed cost, because of long-term financing. Over a given 20 year capital depreciation, the following electric power price increases would be produced by the respective yearly rates of increase:

PRICE TODAY Pf/kWh	YEARLY INCREASE %	FINAL PRICE Pf/kWh
8	3	14,40
	5	21,20
	7	30,88
12	3	21,60
	5	31,80
	7	46,32
16	3	28,80
	5	42,40
	7	61,76

Above approximately 5% annual increase, the pipe diameter which is cost-optimal for today, will be exchanged for the next larger dimension.

5. Interconnected Feed of District Heating Systems

5.1. Simple and Complex Interconnection

With the extension of a district heating system, there are increasing demands on planning and management to find the most economical regime of operation.

Therefore it would appear to be meaningful to distinguish between simple and complex interconnected systems, according to their characteristic features.

The characteristics of a simple interconnected system are:
- one or two feed plants[1]
- same temperature schedules at both plants
- same or differing layout of circulation pumps
- network pump operation with pressure regulation points

The characteristics of a complex interconnected system are:
- three or more feed plants
- load distribution according to operational and economic feed plans
- differing temperature schedules at the feed plants
- differing layout of circulation pumps
- network pump operation with pressure regulation points.

5.2 Presentation of a Complex District Heating Interconnection on the Example of Dinslaken-Duisburg/Walsum

The combined system of the neighboring cities of Dinslaken and Walsum

1. By feed plant is meant: heat donor station (with or without heat exchanger), heating plant, heat and power plant, or power plant with partial heat utilization.

(Walsum since 1 January, 1976, is a part of the city of Duisburg) is characterized by six heat sources with different procurement costs and around thirty network pumpstations for peak load operation.

Since the planners had to determine the capacity of the pipe network in 1961, they proceded on the basis of then known data.

For economic viability, a supply density goal of 46.5 MW/km^2 was set. The most thickly settled part, the center of Dinslaken, measures about 1 km^2. For this area, the distribution network and the generating plants were designed for a copacity of 41 MW (35 Gcal/hr), expandable to 58 MW (50 Gcal/hr).

The first carrying lines were laid from the Dinslaken heating plant to two residential areas in Walsum.

Two years later a heat supply contract was closed with the Walsum power plant so that the extended transport line could be connected with the cooling return lines of the powerplant. With the increase in generating capacity the systematic inclusion of Walsum was undertaken.

The next development was the inclusion of a residential district in the north of Dinslaken, with the connection of heat feed from the Lohberg power plant.

The neighborhood of Hiesfeld was opened and the main distribution lines reinforced by a peak load heating plant.

The city was able to renounce plans for another peak load heating plant in the northwest section due to a contractual arrangement raising the heat supply from the Walsum power plant from 52 MW (45 Gcal/hr) to 81 MW (70 Gcal/hr).

Since further extension exceeded the originally planned distribution capacity, various pump stations were constructed in the heating network.

Within fifteen years the combined supply value climbed to 232 MW (200 Gcal/hr).

By that time the distribution network extended over a service area of 11 km^2.

The network is laid out for a delivery temperature of 130°C.

The residential areas are predominantly operated with a temperature spread of 110°C/50°C; therefore the blockstations must be equipped with mixing pumps. Blockstations and peak load heating plants are remote operated.

By this time the system as shown in Figure 4 had spread far beyond the planned goals in heat supply and surface area served.

5.3 Network Calculation

Computer network calculation, as it is currently carried out for the economical extension of a district heating system with chosen distribution structure, is most preoccupied with the following problems:

- to show the existing load distribution of the system at peak heat requirement
- to evaluate the local sources of supply
- to calculate appropriate measures for increased distribution performance
- to determine security measures in case of emergency.

Output data of the calculations are:

- network data, (lead routes, lead lengths, interior diameters, geodetic height of nodes, network roughness or pipe roughness, position and performance of pressure regulation units and pressure control points)
- consumer data, (position of outputs in the network, specified output pressures)
- medium data, (temperatures, density, kinematic viscosity)
- feed data (graphs or performance charts for circulation pumps, temperature schedules, boiler performance).

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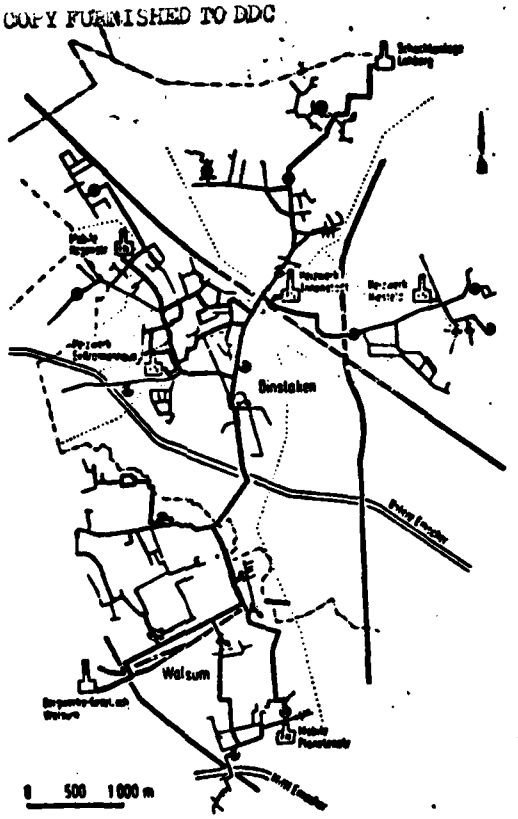


Figure 4. Map of the Dinslaken/Walsum District Heating System

- district heating system network
- heating plant
- heat source
- principal heat source
- pump station
- pressure reduction unit
- pump station with pressure reduction unit
- shut-off valves
- ..... domain of influence of the heat sources as discussed in section 6.2

The respective calculation results give a presentation of the momentary status of the system in operation.

Table 3 shows a computer printout for a sample calculation comprising a three-part data list (junction list, delivery lead list, return lead list).

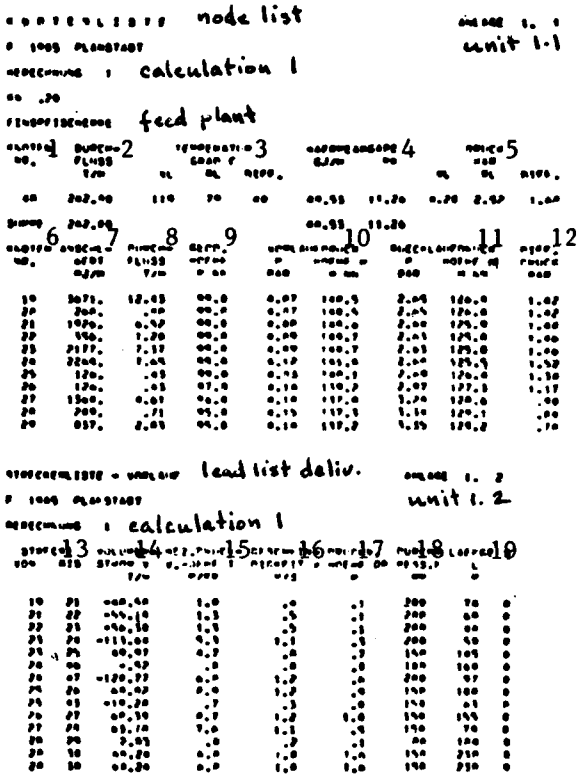
6. Problems for Computed Analysis

6.1 Comparison Measuring

In order to represent the actural hydraulic conditions of a complex district heating system by network analysis, it is necessary to perform a comparison measurement ofver several hours, at a time of high network load. The following data are simultaneously determined:

- delivery and return pressures, temperatures and flows of the feed plant (for example, half-hourly),

Table 3. Printout of a computer network calculation with one feed plant (48 nodes)



1) node number
2) flow tons/hr
3) temp. ^{0}C, deliv., return, difference
4) heat supplied, Gcal/hr, MW
5) pressure, deliv., return, diff.
6) node number
7) supply, MJ/hr
8) flow, tons/hr
9) geodetic height, M NN
10) deliv. pressure, p. bar, height, M NN
11) return press., p. bar, height, M NN
12) pressure difference, bar
13) lead, from, to
14) volume, delivery, tons/hr
15) network pres., deliv., height, m/MW
16) flow rate, m/sec
17) pres., deliv., height, (illeg.), m
18) flow, (illeg.), MW
19) lead section length, m

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- delivery and return pressures, temperatures and flow at large volume customers (for example, half-hourly),
- the delivery and return pressures at characteristic nodes (measuring units, large customers, network pressure regulation units) by means of pressure recorders.

Although sudden fluctuations in load during the comparison measurement cannot be neglected, system steady state should in any case reestablish in an hour.

A sufficient number of pressure measuring points and highest possible pressure drop are the preconditions for a valid evaluation of the measurements.

The following data for three quite different medium-to large urban distribution networks can serve as a basis for examination.

network	length (delivery)	supply	number of house-stations	number of pressure measurement points	max. pressure drop at time of measurement (delivery)	
	km	MW			bar	m/km
A	150	232	6,600	30D+42R	6.7	10.6
B	20	172	160	13D+13R	6.0	8.2
C	43	320	630	9D+ 9R	4.6	9.9

(D - delivery; R - return)

Usually two operating conditions are evaluated, which can then be reproduced in the comparison calculation.

Experience shows that a comparison calculation can be considered valid when the discrepancies of calculated and measured pressures do not exceed the limit

$$a = \pm\sqrt{\Delta P_{max}} \text{ , expressed in m}$$

The quantity ΔP_{max} is understood to be the maximum pressure drop to be found at time of measurement (in delivery or return side) between the feed plant and its boundary of influence, expressed in bars.

6.2 Flow Resistances

The flow resistance of a lead in the distribution network is a combination of the resistance in straight pipes and the incidental resistances which are caused essentially by curves, branches, outlets, and insertions (shut-off valves, compensators, measuring devices).

There are three possibilities for formulation these additional resistances, as follows:

a) compilation of the individual friction coefficients from specification documents and tables,

b) formation of an average coefficient of friction ζ for the entire network, statistically or by comparison measurement,

c) calculation of an average roughness value k_n for the whole network or for individual leads, by comparison measurement.

Procedures a and b calculate with the given pepe roughness k and increase the actual lead lengths, by the coefficient of friction, to equivalent lengths.

Procedure c calculates with the actual lead lengths and an equivalent pipe roughness (= network roughness k_n), which is derived in the same way as for water and gas networks, by comparison measurement.

Since the calculation with network roughness k_n

- demands no assumptions concerning pipe roughness k,
- leads most quickly to a balance between comparison calculation and comparison measurement,
- is less variable with system load than is the friction coefficient ζ ,

the authors give preference to procedure c for the netword calculation.

Figure 5 acurately shows the dependency of the quantities ζ and k upon the flow rate and thereby upon the system load.

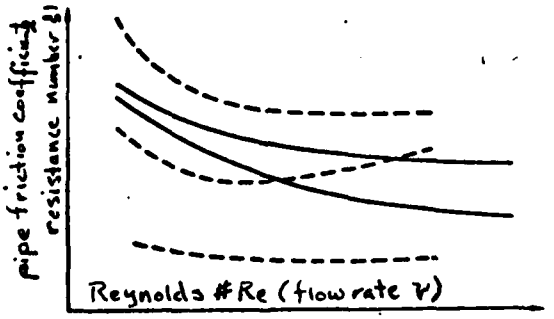

Figure 5. Variation of incidental resistances ζ (bends, elbows, curvatures) - - - - and of combined resistances k_n (network roughness) ————

In the 13 district heating networks determined to this date by means of comparison measurement and comparison calculation, the network roughness lies between 0.15 mm and 0.30 mm.

Since pipe roughnesses in published tables fluctuate mostly around 0.05 mm, there is a factor of increase for the incidental resistances in the network of from 3 to 6. By comparison, for cold water networks the factor of increase between pipe roughness and network roughness is 10 times higher.

6.3 Temperature Influences

Network calculation programs do not, as a rule, include any mathematical consideration of the following complex factors of influence:
- thermal efficiency losses of the network in delivery and return,
- temperature differences at a given time between the feed plants.

Losses related to thermal efficiency are at their smallest on cold winter days and at their maximum of warm summer days. Since the network computation is carried out basically for the case of a coldest day, thermal efficiency losses can be neglected, except in cases involving great transmission lengths, or where reliable temperature measurements indicate more than 4% temperature decrease over the length of delivery.

For example, for a distribution network with operating temperature 120°C/70°C and a delivery temperature decrease to 116°C between feed plant and network periphery, and increasing flow-through of hot water (given in tons/hour) at a household must compensate for the decreasing temperature spread; this can be shown clearly enough be dividing the network into three zones. Figure 6 shows a simplified case with three coustomers, whose heat requirement is 1 MW each.

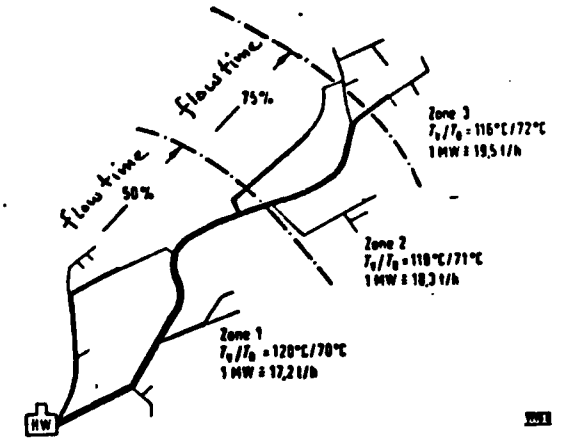

Figure 6. Increase in hot water requirement, in tons/hour, as delivery temperature decreases toward network periphery

If the feed plants in an interconnected district heating system operate at different temperature spreads, the respective domains of influence and the temperature dependent quantities (water density in delivery and return, behavior of hot water flow-through with respect to heat required) must be

considered, in order to determine a valid distribution of water volumes in the system.

In the table below, the temperature characteristics of the six heat sources of the Dinslaken/Walsum interconnected system, at peak load operation, are presented.

Table 4. Yield and temperature characteristics of the feeds for the Dinslaken/Walsum system

heat source	boiler capacity MW	Gcal/hr	temperatures deliv. °C	return °C
Walsum powerplant (supply)	81	70	128	55
Lohberg powerplant (supply)	19	16	124	48
city center heat plant	35	30	120	56
peak load heat plant Hiesfeld	12	10	110	58
central heating, Evang. Hospital	6	5	110	58
moble unit, Hagenstrasse	6	5	100	55
moble unit, Planetenstrasse	6	5	100	55

The spatial boundaries and the distribution of water volumes for the influence domains of the respective feed plants are determined by iterative calculation steps:

1. The first network computation is undertaken using the temperature characteristics of the main feed plants.
2. The resulting boundaries of the influence domains (the flow rate in boundary lead sections approaches zero) are noted down in the network calculation plan and fed to the computer.
3. The second network computation is performed using the actual temperature values of the feed plants.
4. The resulting changed set of influence domains are noted in the network calculation plan and fed to the computer.
5. For the third and final network computation, averaged influence domains are determined from step 2 and step 4.

In Figure 4, the domains of influence of the Dinslaken/Walsum interconnected system are indicated, for the case of a cold winter day. ($Q_n = 0.9 \cdot Q_{n\,max}$)

Since for a complex district heating network, a computer printout data list as exemplified by Table 3 is not sufficient to enable a quick or comprehensive grasp of the related pressure and flow characteristics, in certain circumstances the data are represented in pressure distribution diagrams and network calculation plans.

Figure 7 shows a high-speed printout of pressure distribution in the calculation of a chosen lead layout. Figure 8 shows an excerpt of a schematic network calculation plan.

7. Closing Observations

The expansion of urban district heating systems, promoted by government investment and motivated by models for community energy sharing, leads to increasingly complex distribution networks.

The notion of "complexity" should be understood to refer to the economic viability as well as the technology involved; which is to say that a strong boundary-cost analysis for planning and operation alternatives is emphasized.

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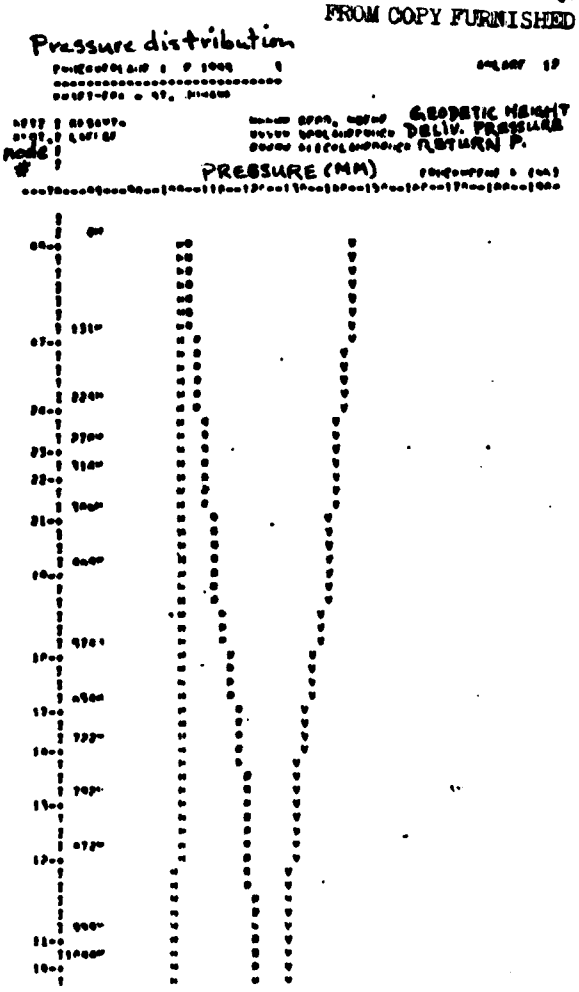

Figure 7. Pressure distribution for a lead between feed and end node

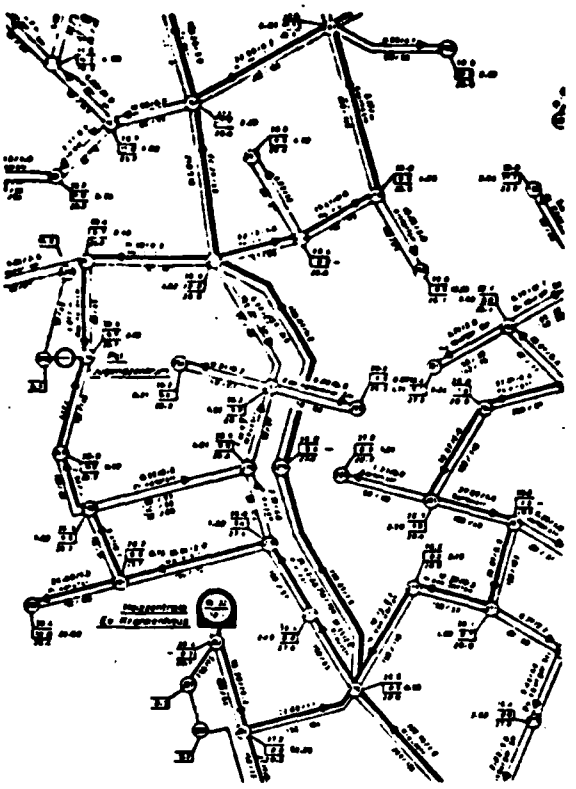

Figure 8. Presentation of pressure/ flow distribution in delivery and return

Standard computer network computation is insufficient to represent the operation of a complex district heating network.

The present exposition takes a closer look at the following criteria, which have a strong influence on planning:

- dynamic development of line costs,
- improvement of calculation output through comparison measuring,
- determination of the lead resistances,
- consideration of unequal feed temperatures.

Once all data for hydraulic conditions of the district heating network in its present state are accumulated and prepared for computer network calculation, various plan circumstances can be quickly and directly simulated.

The following planning problems are listed in ascending order of difficulty:

- hookup for a new customer
- layout of a lead
- layout of a pumping unit
- determination of pressure control points
- insertion of a new feed
- alteration of temperature schedules.

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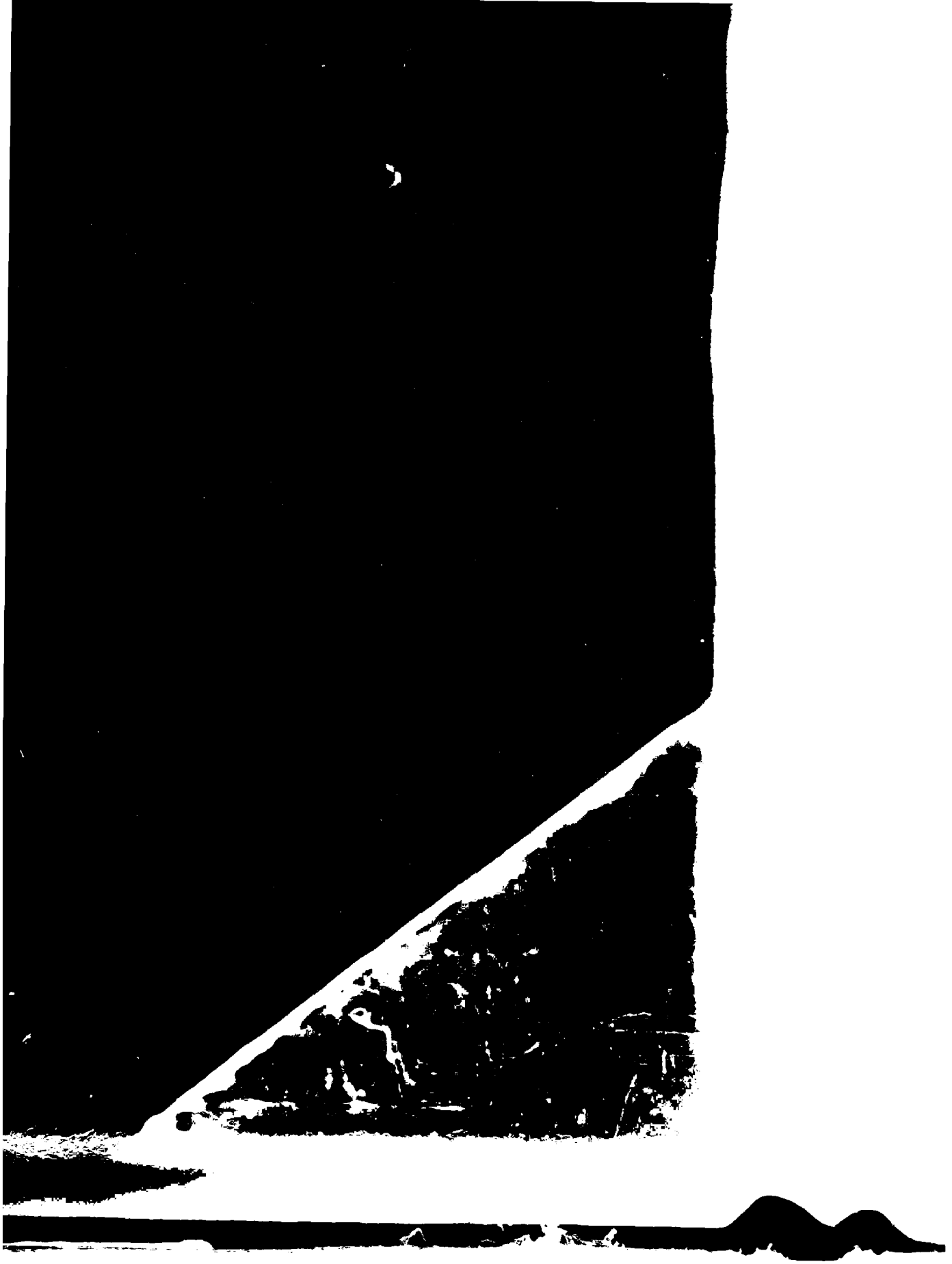
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